N. S. HARDING & ASSOCIATES

Reagent Characterization and Bench-scale Combustion Testing Program

N. S. Harding

Final Report

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Covol Fuels
Division of Headwaters, Inc.

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1019 East Eaglewood Drive
North Salt Lake, UT 84054
Tel: (801) 294-5030 Email: nsharding@attglobal.net Fax: (801) 294-5030

EXECUTIVE SUMMARY

Operators of power stations always have questions concerning the use of a new or altered fuel. Even though a coal has been treated with a very small quantity of reagent, questions linger as to what the reagent has done or might do to affect the combustion process. To provide factual responses to these types of questions, Covol Fuels desired that laboratory and bench-scale combustion tests be run on two reagents (298 and 298-1) at two dosage rates (*normal* [2 lbs solids and 20 lbs water per ton coal] and *10X* [20 lbs solids and 20 lbs water per ton coal]) and the results compared to the untreated River Hill coal.

Penn State University and Advanced Fuel Research completed the fuel characterization tests on the five fuels. Penn State then performed the bench-scale testing on these fuels in their drop-tube furnace. Fuel characterization tests included proximate, ultimate, ash mineral, heating value, ash fusion temperatures, size distribution, volatiles heating value, SEM microscopy, BET surface area, petrography, fluorescence, reflectance and thermo-gravimetric-fourier transform infrared spectroscopy analyses. The bench-scale tests provided information on gaseous emissions including CO, CO_2, NO_x, and SO_2 under fuel-rich and fuel-lean operating conditions.

The results of the program clearly documented the following:

- The addition of Covol 298 or 298-1 reagents to River Hill coal at *normal* (2 lbs solids/ton coal) or *10X* (20 lbs solids/ton coal) dosage rates did not result in any adverse effect on fuel characteristics or combustion properties.
- Reagent addition did show a greater number of small particles agglomerating around the surface of larger coal particles suggesting that the reagent was acting as a dust suppressant and was effectively dispersed on the parent coal. This agglomerating effect increased as the dosage rate was increased.
- Common coal analyses performed on all fuels showed that the four reagent-added fuels had values within one standard deviation of the parent coal for nearly all analyses.
- Combustion and deposition parameters calculated for each of the fuels were nearly identical suggesting that operation with the reagent-added fuels would be similar to the parent coal.
- Gaseous emission products from pyrolysis testing were similar between all fuels. Although the amount of NO_x precursors, ammonia and hydrogen cyanide, were slightly reduced during pyrolysis, the final NO_x emission levels measured from the drop-tube tests were not statistically different.

The following recommendations are made:

- The larger, pilot-scale testing (>100 lbs/hr) should be investigated to confirm these laboratory and bench-scale results. These tests could be combined with other testing on a reduced number of fuels.
- Covol Fuels should continue to pursue fabricating their own bench-scale combustion facility to perform characterization tests on other coals utilizing these and new reagents.

1.0 INTRODUCTION

Operators of power stations, primarily electric utilities, always have questions concerning the use of a new or altered fuel. Even though a coal has been treated with a very small quantity of a reagent, questions will linger as to what the reagent has done or might do to affect the combustion process. These questions can be related to potential differences in operation or impacts on equipment or related to whether the emissions from the plant will be altered. However, if there is an impact from the reagent addition, it should not necessarily be assumed that the impact would be negative. For example, differences in combustion between a parent coal and a reagent-treated synfuel might be positive, e.g., lower unburned carbon, lower NO_x, etc.

Earlier combustion tests with a previous 298-series reagent showed there were no measurable differences between a parent coal and synthetic fuel in the way the fuel burned. The most recently developed reagent, 298-1, is slightly different in chemical composition from the original 298 reagent. Therefore, Covol Fuels, a division of Headwaters, Inc., desired that additional laboratory and combustion tests be run on the new reagent, the original reagent and the results compared to the untreated parent coal. While pilot-scale combustion testing will not resolve all the questions that might arise, it is thought that such testing can provide a suitable foundation to make more informed judgments or to come to some opinion regarding the new synthetic fuel, based on facts and data.

Therefore, the objective of this program was to determine whether there is a significant effect on the combustion performance of a fuel treated with Covol 298 and 298-1 reagents through laboratory and pilot-scale combustion testing. To accomplish this objective, an evaluation program was developed and requests for proposals were sent to the following five organizations:

- Brigham Young University Advanced Combustion Engineering Research Center
- Pennsylvania State University Energy Institute
- University of North Dakota Energy and Environmental Research Center
- Advanced Fuel Research
- Reaction Engineering International/University of Utah

The evaluation program included five different fuels and three main tasks. The five fuels were:

- River Hill bituminous coal with no reagents added (baseline)
- River Hill coal treated with a normal dosage of Covol 298 reagent
- River Hill coal treated with a normal dosage of Covol 298-1 reagent
- River Hill coal treated with a 10X dosage of Covol 298 reagent
- River Hill coal treated with a 10X dosage of Covol 298-1 reagent

Currently, Covol adds the reagents at a 2 lbs solid/ton coal dosage rate. This is defined as the "*normal*" dosage rate; therefore, the "*10X*" dosage rate is 20 lbs solid/ton coal.

The three main tasks to be completed on each of the five fuels were:

1. Fuel Characterization
2. Bench-scale Combustion Tests (<10 lb/hr)
3. Pilot-scale Combustion Tests (>100 lbs/hr)

Proposals were received from all organizations except BYU Advanced Combustion Engineering Research Center who opted to not respond. Advanced Fuel Research only proposed to do some fuel characterization studies unique to their company. The other three organizations provided proposals covering all fuels and all tasks.

After an in-depth and critical review of all proposals, it was decided to award the Fuel Characterization and Bench-scale Combustion Tests (Tasks 1 and 2) to Penn State University Energy Institute (PSU), to have Advanced Fuel Research (AFR) perform their TG-FTIR (Thermal Gravimetric-Fourier Transform Infrared) spectroscopy analyses (Task 1) and to award the pilot-scale testing, if deemed necessary, to Reaction Engineering International/University of Utah. This decision will be based on a review of the data and results from Tasks 1 and 2.

Final reports have been received from Penn State for Tasks 1 and 2 and from AFR for their Task 1 testing. This report, therefore, is a synopsis of the more detailed reports and provides an overview of the conclusions from these studies and provides recommendations for further evaluations.

2.0 TEST PROGRAM

The test program detailed in this report consists of the first two tasks in the original program: Fuel Characterization and Bench-scale Combustion Tests. The requested analyses and tests for each task will be discussed separately.

2.1 Fuel Characterization – Task 1

Task 1 was designed to evaluate fuel analyses and fuel preparation and handling conditions of the five fuels. The fuels needed to be crushed and, where appropriate, pulverized to standard power generation size of 70% passing through a 200 mesh screen (74 micron) with less than 0.5% greater than a 50 mesh screen (297 micron).

The analyses requested in Task 1 constituted routine and advanced analytical tests performed on most coals. In addition, more fundamental tests were requested which would provide information on combustion characteristics, particle surface phenomena, devolatilization products and potential emissions. None of the tests were designed to determine any chemical change to the fuel as a result of the reagents, as these are already well documented. Rather, these analyses could provide boiler personnel facts regarding the potential changes to their operating system due to synfuel usage. Therefore, the following characterization tests were to be completed on all five fuels:

1) Screen analysis (+1/4 inch and Nos. 4, 10, 18, 35 and -35 mesh screens) of crushed material (wet screen, as necessary)

2) Fuel analyses:
   a) Proximate
   b) Ultimate
   c) Ash mineral
   d) Heating value
   e) Ash fusion temperatures (oxidizing and reducing)
3) Size distribution of pulverized fuel
4) Volatiles heating value
5) Petrographic analysis
6) BET surface area
7) Scanning electron microscopy ("as-received" and pulverized product)

In addition, PSU recommended and completed the following characterization tests:

8) Reflectance analysis
9) Fluorescence analysis

Advanced Fuel Research is a small business focusing on specialty analyses in the energy arena. They have developed a technique for measuring the off-gasses from fuel devolatilization tests. As a result, AFR proposed and completed the following fuel characterization analyses:

10) Proximate analysis from TGA test
11) Tar yield during devolatilization
12) Gas analyses during devolatilization, including:
    a) Carbon monoxide
    b) Carbon dioxide
    c) Ethylene
    d) Hydrogen cyanide
    e) Ammonia

This suite of analyses and specialized tests were completed as Task 1. The results will be discussed in Section 3 of this report.

2.2 Bench-scale Combustion Tests – Task 2

Once the fuels were characterized completely from Task 1, they underwent some fundamental combustion testing. The purpose of these tests was to address the following issues:

1. Does the reagent affect the devolatilization of the River Hill coal under oxidizing or fuel rich conditions?

2. Does the reagent affect the overall NO_x production, and equally important, does the reagent impede or facilitate the complete burnout of the char?

3. Are there any different gases produced as a result of the addition of the reagent when compared to the baseline coal?

4. Finally, can enough be learned from bench-scale testing to substantiate reasonable combustion conclusions with regard to commercial operation?

To evaluate these issues, bench-scale testing was recommended. The size of the facility selected was such that accurate, representative data could be collected. Tests were completed at different stoichiometric ratios to investigate the effects of low-NO_x firing conditions as well as pre-NSPS (New Source Performance Standards) conditions. In all cases, final burnout air was added such that the overall stoichiometric ratio was constant at 1.20, meaning 20% excess air. The stoichiometric ratios tested were 1.20 (fuel-lean), and 0.85 (fuel-rich). The final burnout air (required for the fuel-rich test) was added so that a minimum of 0.5-second residence time was available to complete combustion prior to about 1800°F gas temperature. The Penn State drop-tube furnace met these criteria and was used for Task 2 testing. A schematic diagram of the drop-tube facility is shown in Figure 1.

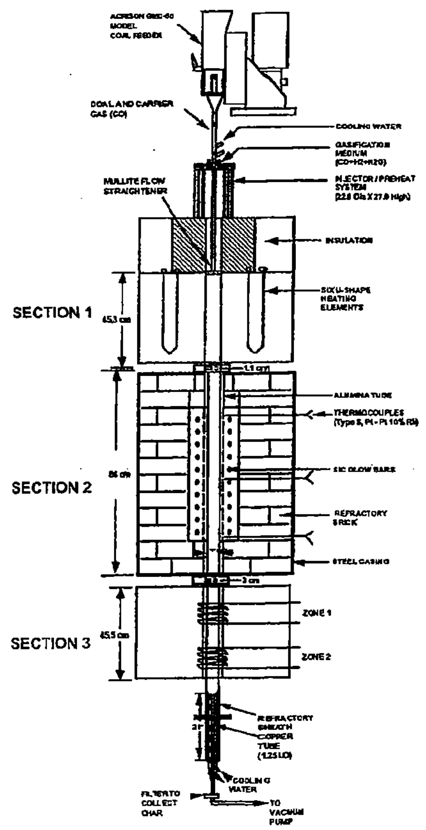


Figure 1. Schematic diagram of Penn State drop-tube furnace.

The data collected during each test included:

1) Operating conditions
2) Flue gas composition (NO_x, CO, CO_2, O_2, SO_2)
3) Gas chromatography analysis of flue gas
4) Furnace wall temperature profile
5) Combustion gas temperature profile
6) Char/ash composition:
   a) Proximate
   b) Ultimate
   c) Scanning electron microscopy
7) Residence time estimation

An important outcome of Task 2 was to conclude whether this scale of testing could be of value to Covol in further combustion trials with these reagents or in the evaluation of new reagents. Therefore, following these bench-scale combustion tests, an analysis of Tasks 1 and 2 was done and final recommendations made before proceeding with Task 3.

3.0 RESULTS AND DISCUSSION

This section will provide a summary of the results of the fuel characterization work completed at Penn State University and at Advanced Fuel Research (Task 1) and the bench-scale combustion tests completed at Penn State (Task 2). Details of each company's work can be found in its individual report.

3.1 Sample Preparation

Sample preparation is perhaps key to the overall success of the entire project. The details of how each sample was prepared are presented next. Covol sent three drums of River Hill coal to Penn State for preparation of all samples. Covol personnel aided Penn State in the preparation of the reagent dosages and mixing of the different reagents with the baseline coal. The procedure used was as follows:

1) Crushed all three drums of River Hill coal to minus 8 mesh per ASTM 2013;
2) Riffled the coal into eight equal and representative samples;
3) Shipped one sample back to Covol Fuels;
4) Retained two samples and labeled them as the Head coal samples;
5) Each of the remaining five samples were prepared as follows:
   a) For the "*normal*" dosage rate, a mixture of 0.2 pounds neet 298 reagent and 0.8 pounds water was sprayed onto each 99 pounds of a Head coal sample while being mixed in Penn State's ribbon mixer;
   b) For the "*normal*" dosage rate, a mixture of 0.2 pounds neet 298-1 reagent and 0.8 pounds water was sprayed onto each 99 pounds of a Head coal sample;

c) Two pounds of neet 298 reagent were sprayed onto each 99 pounds of a Head coal sample to produce the 298-10X product ("*10X*" dosage rate);

d) Two pounds of neet 298-1 reagent were sprayed onto each 99 pounds of a Head coal sample to produce the 298-1-10X product ("*10X*" dosage rate); and

e) Two pounds of water were added to each 99 pounds of a Head coal sample and mixed in the ribbon mixer. This sample was labeled as the Parent coal sample.

6) Two approximate 4 pound aliquots were riffled from each of the five samples and one was sent to Covol Fuels and the other to Advanced Fuel Research; and

7) The remaining amount of each sample was returned to Covol Fuels.

The coal samples were then pulverized for use in the drop-tube reactor (DTR) tests in Task 2 using a bench-scale pulverizer. The following procedure was used to prepare the samples for the DTR testing:

1) Process the samples through the ≈ 6 lb/h Holmes Model 501XL mill, set for minus 60 mesh (250 μm);
2) Screen the resulting sample at 200 mesh (74 μm);
3) Calculate, by mass, the percent passing 200 mesh;
4) If there is 70-75% passing, then use the sample;
5) If there is less than 70-75% passing, take the oversize material and run it through the mill again and rescreen the product at 200 mesh. Calculate the new percent passing 200 mesh. If it is between 70-75%, use the sample. If not, then repeat the process until about 70-75% of the original sample passes 200 mesh; and
6) Record the amount passing through 200 mesh and then determine final size distribution for each sample.

An additional five coal and reagent samples were prepared in the ribbon mixer using twice the quantity of water than that used when preparing the original fuels. These samples were for petrographic and optical characterization tests and were labeled "Remix".

3.2 Fuel Characterization – Task 1

3.2.1 Penn State University

The majority of the fuel characterization work was completed at Penn State University (PSU) located in State College, PA. PSU has established the Energy Institute and is one of the preeminent laboratories actively involved in combustion testing and analytical research.

As noted in the previous section, PSU completed the detailed analyses of the five coal samples. All analytical techniques used by Penn State were according to documented ASTM procedures or accepted industry practices. The details are found in the Penn State Task 1 report.

The analyses completed on all samples include those routinely done on fuel samples at utility stations. In addition to the routine analyses, special analyses were completed including surface area and volatile matter heating value. Table 1 summarizes the analytical results for all samples by listing the parent coal (no reagent) analyses and then the average and standard deviation for the reagent-addition samples (4 in total).

The data results clearly demonstrate that the addition of either of the reagents, even at ten times the recommended dosage rate, had essentially no effect on the routine analyses completed for all fuels utilized in power generation. This is to be expected, as the dosage rates of the reagents are so small relative to the mass of coal. In nearly all cases, the average coal+reagent analysis falls within one standard deviation of the parent coal analysis. This suggests at least two points: 1) There is good agreement between all four samples of coal+reagent even for the difficult analyses such as particle size (D_{50}), volatile matter heating value, and surface area; and 2) None of the coal+reagent samples differ significantly from the baseline parent coal.

This result is even further substantiated by calculating the principal combustion parameters used to estimate deposition tendency and combustion performance in a boiler. The primary parameters are the base-to-acid ratio, the slagging factor and the fouling factor. These parameters are calculated as follows:

$$\text{Base/Acid Ratio} = (CaO+Fe_2O_3+K_2O+MgO+Na_2O)/(Al_2O_3+SiO_2+TiO_2) \quad (1)$$

$$\text{Slagging Factor} = \text{Base/Acid} * \%S \quad (2)$$

$$\text{Fouling Factor} = \text{Base/Acid} * \%Na_2O \quad (3)$$

where the base/acid ratio uses the ash analyses, the %S is the sulfur amount determined in the ultimate analysis and the $\%Na_2O$ is again from the ash analysis.

Table 2 lists these three calculated parameters for the parent coal and for each of the coals having reagent addition. Again, the results clearly show that the reagent is not having any appreciable effect on the estimated combustion or deposition performance of the fuel.

Penn State also completed more advanced analytical techniques on each fuel including petrography, scanning electron microscopy (SEM), fluorescence and reflection analyses. The petrographic mineral analyses for all fuels are listed in Table 3 and clearly show similar results as the ASTM analyses – there are no significant differences in mineral content between the parent coal and any of the coals with reagent addition. This is also true of the reflectance value for each fuel.

One clear result of the SEM and fluorescence analyses was that the coals with the reagent added did result in more small particles being agglomerated around larger coal particles. An example is shown in Figure 2. The top portion of this figure shows a typical SEM photograph of the parent coal, the middle shows the 298 reagent at the normal dosage, while the lower portion is typical of the 298 reagent at the 10X dosage rate. This trend was also noted for the 298-1 reagent. This observation suggests that the reagent could act as a fugitive dust suppressant and that it was effectively dispersed on the parent coal. This agglomerating effect increased as the dosage rate was increased as shown in Figure 2.

Table 1. Analytical Summary of Coal and Reagent Samples

	Parent Coal	Coal Plus Reagent (Average)	Standard Deviation
Proximate, As Received			
Moisture	0.6	0.8	0.1
Volatile Matter	21.4	21.4	0.4
Ash	15.8	16.9	0.7
Fixed Carbon	62.2	60.9	0.9
Ultimate, Dry			
Carbon	73.8	73.1	0.6
Hydrogen	4.2	4.2	0.1
Nitrogen	1.4	1.3	0.0
Sulfur	1.6	1.6	0.1
Oxygen	3.1	2.8	0.2
Ash	15.9	17.1	0.7
Heating Value, Btu/lb			
Coal	13009	12904	75
Volatile Matter	2848	2674	123
BET Surface Area, m^2/g			
Coal	1.156	0.727	0.232
D_{50}, µm	42.8	44.2	4.7
Ash Analysis, wt % of ash			
Al_2O_3	26.7	26.0	0.5
BaO	0.07	0.06	0.00
CaO	2.19	2.10	0.05
Fe_2O_3	9.83	9.65	0.22
K_2O	2.29	2.20	0.05
MgO	0.89	0.86	0.01
MnO	0.02	0.02	0.00
Na_2O	0.21	0.23	0.01
P_2O_5	0.01	0.03	0.00
SiO_2	52.7	51.5	0.7
SrO	0.05	0.05	0.00
TiO_2	1.49	1.45	0.03
SO_3	1.61	1.51	0.15
Ash Fusion Temperature - Reducing, °F			
Initial	2625	2624	10
Softening	2660	2661	19
Hemispheric	2695	2700	16
Fluid	2750	2744	15
Ash Fusion Temperature - Oxidizing, °F			
Initial	2740	2743	5
Softening	2760	2770	8
Hemispheric	2800	2793	10
Fluid	+2800	+2800	0

Table 2. Calculated Combustion Parameters for all Fuels Tested

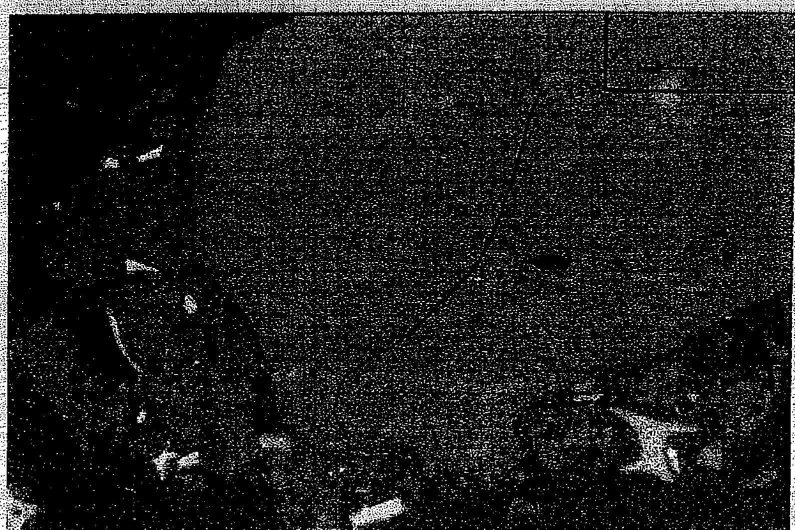
Parameter	Parent Coal	298 Normal	298-10X	298-1 Normal	298-1 10X
Base/Acid Ratio	0.19	0.19	0.19	0.19	0.19
Slagging Factor	0.30	0.30	0.33	0.30	0.28
Fouling Factor	0.04	0.04	0.05	0.04	0.04

Table 3. Measured Petrography, Maceral and Reflectance Analyses

	Head Sample	Parent Coal	298 Normal	298 - 10X	298-1 Normal	298-1- 10X
Vitrinite	74.4	73.7	75.5	72.5	74.7	73.5
Sporinite	0.0	0.4	0.1	0.0	0.0	0.0
Resinite	0.0	0.0	0.0	0.0	0.0	0.0
Cutinite	0.0	0.0	0.0	0.0	0.0	0.0
Fusinite	1.8	1.8	2.0	2.2	2.0	1.6
Semifusinite	7.0	7.9	5.2	8.0	7.6	8.0
Macrinite	0.3	0.3	0.3	0.4	0.2	0.3
Micrinite	3.7	4.9	6.4	5.1	3.9	5.0
Inertodetrinite	2.0	1.4	0.7	0.8	1.2	1.5
Mineral Matter	10.8	9.6	9.8	11.0	10.4	10.1
Reflectance	1.25	1.20	1.18	1.14	1.18	1.18

Parent

298
Normal



298 – 10X

Figure 2. Influence of 298 reagent on small particle agglomeration to large particles.

3.2.2 Advanced Fuel Research

As mentioned in the Sample Preparation Section 3.1, Penn State sent riffled samples of each of the 5 fuels to Advanced Fuel Research for specialty analyses including TG-FTIR (Thermogravimetric-Fourier Transform Infrared) spectroscopy. The procedure for this analysis consists of measuring the weight change and evolved gaseous composition of samples as they are heated in an inert environment. In essence, this provides an analysis of the pyrolyzing gases as a function of temperature. The objective of these tests was to determine if the reagent was influencing the release of tars, carbon monoxide, carbon dioxide, hydrocarbons, ammonia and hydrogen cyanide from the coal matrix during the early stages of combustion such as would be found in the near-burner region of a boiler where there is insufficient oxygen to completely burn the fuel (i.e., fuel-rich, low-NO_x firing condition).

The results of the AFR study showed that the addition of either reagent to the parent coal did not cause any significant change in the pyrolysis behavior of the coal even at the 10X dosage rate. As mentioned earlier, the results of these tests provided an analysis of the ammonia (NH_3) and hydrogen cyanide (HCN) that are evolved as the coal undergoes pyrolysis. Ammonia and hydrogen cyanide are known to be the precursors of fuel-NO_x formation in coal-fired boilers. And, as fuel-NO_x accounts for about 70-80% of the total NO_x formed in these systems, altering the amount of ammonia and hydrogen cyanide released could have a significant impact on the final NO_x emissions. Figures 3 and 4 show the release of ammonia (Figure 3) and hydrogen cyanide (Figure 4) as a function of sample temperature for both reagents at the 10X dosage rate.

It appears from Figure 3 that the 298 reagent is causing the ammonia to release earlier (at a lower temperature) than either the parent coal or the coal with 298-1 reagent. However, the final amount of ammonia released is only about 10% lower than the parent coal. The 298-1 reagent has inhibited the release of ammonia compared to the parent coal throughout these pyrolysis tests.

The reverse trend is noted for the release of hydrogen cyanide (Figure 4). The 298-1 reagent has caused the HCN to be evolved at higher rates early in the pyrolysis process, but then the overall release is comparable to the parent coal. The 298 reagent has reduced the amount of HCN released throughout the test resulting in about a 25% reduction in overall HCN yield compared to the baseline parent coal.

It was not possible to do a complete nitrogen balance during these tests because the residual char could not be collected for analysis. Also, these tests are completed on very small samples; therefore the error of any one measurement may be relatively high. In discussing this with AFR personnel, they felt that the tests were representative of other samples they have done using similar Pennsylvania coals.

Finally, even these changes in ammonia and hydrogen cyanide release patterns do not appear to significantly influence the final combustion NO_x generated as will be shown in the bench-scale testing completed at Penn State. All other species measured produced similar results; that is, neither reagent significantly altered the pyrolysis products of the parent coal even at the high dosage rates.

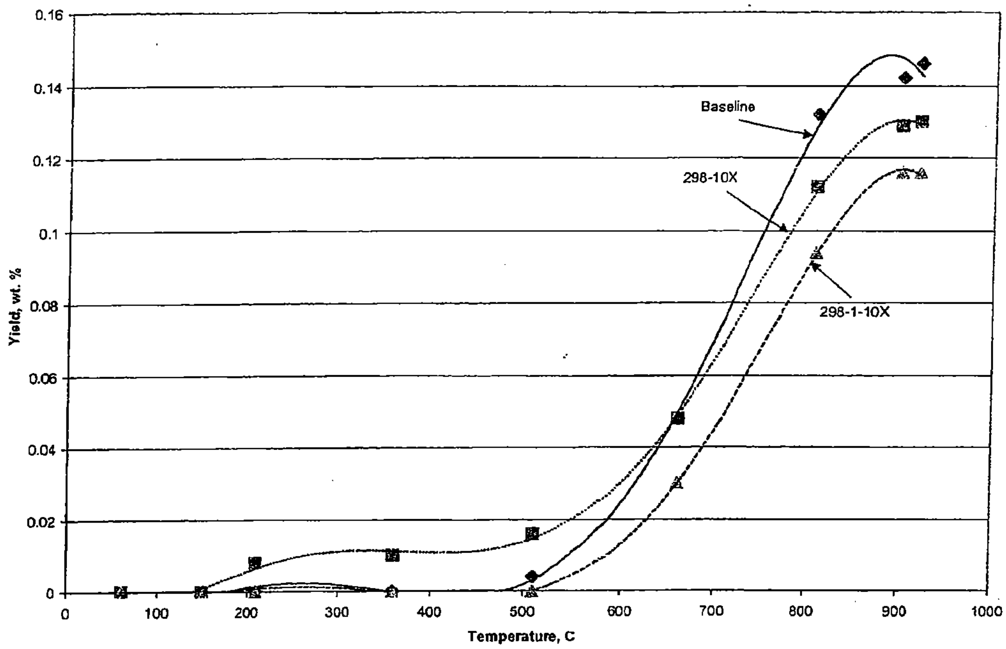


Figure 3. Ammonia release during pyrolysis.

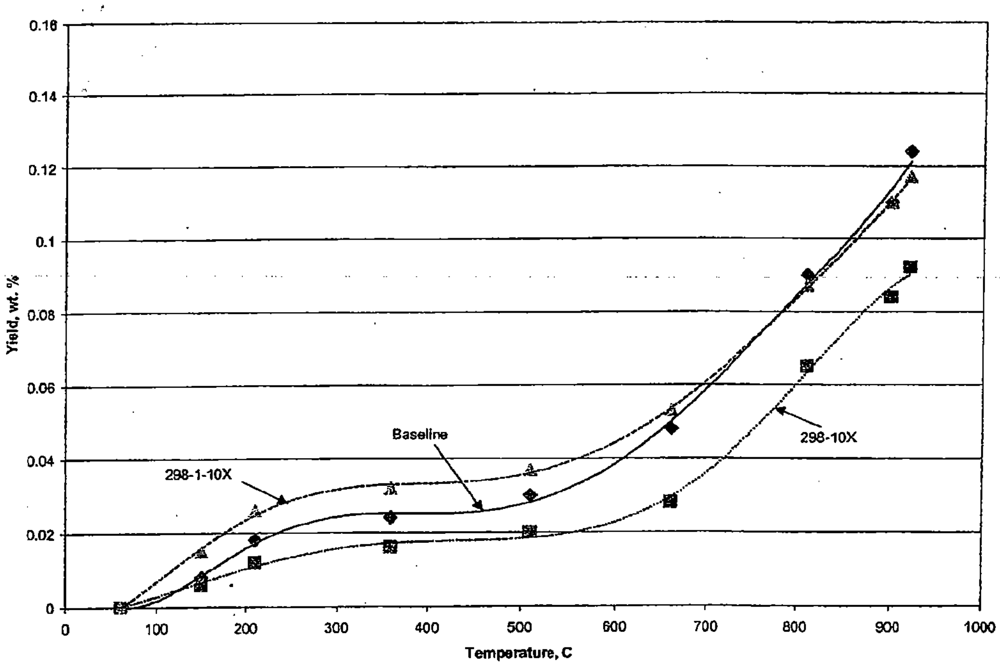


Figure 4. Hydrogen cyanide release during pyrolysis.

3.3 Bench-scale Combustion Tests – Task 2

Following the fundamental analyses completed at Penn State and Advanced Fuel Research, it was determined that bench-scale combustion tests should be done at the Penn State Energy Institute using their drop-tube furnace (see Figure 1). Bench-scale tests were selected as the first series of tests that begin to simulate combustion conditions in operating boilers. These tests are done in small quantities and in small furnaces so that operating conditions and the environment can be held constant.

3.3.1 Penn State University

The drop-tube furnace at Penn State University Energy Institute was selected for these bench-scale tests because it can simulate the fuel heating rates, temperature profiles, and particle residence times of pulverized coal-fired utility boilers on a very small scale. The fuels were fed at a rate of about 0.33 g/min and tested at two different stoichiometric ratios: 1.2 (fuel lean) and 0.85 (fuel rich). As noted in the Test Program Section 2.0, the main objective of these bench-scale tests was to determine if any combustion difference could be substantiated between the baseline parent coal and the reagent-addition fuels.

A combustion test of each fuel was conducted in the drop-tube reactor (DTR) at a temperature of about 3000°F (1650°C), well above the desired 1800°F. Both staged and non-staged air conditions were tested, for a matrix of ten tests. The average test length was approximately one hour. Oxygen, carbon monoxide, carbon dioxide, sulfur dioxide and oxides of nitrogen were recorded using a continuous emissions monitoring system. Gas samples were collected for off-line gas chromatographic analysis of light hydrocarbons. Char/ash samples were collected and characterized using scanning electron microscopy.

Figure 5 shows the gaseous emissions from the fuel-lean, no air-staging tests, while Figure 6 highlights the results of the fuel-rich, staged combustion tests. Note the scale factor for the different gaseous species on each of the figures. The gaseous emissions from all five fuels show quite consistent results. Because burnout air is added downstream in the staging tests, the CO_2, SO_2, and O_2 results are similar. The CO emissions for all tests are relatively high, especially the non-staging tests where levels over 1200 ppm were measured. These high CO values suggest that there was not sufficient residence time to completely burn the fuel. This was supported by SEM micrographs of the char/ash collected that had unburned carbon in the samples. Because of air in-leakage and cooling problems with the full drop-tube furnace, the lower section was removed and not used. This reduced the estimated residence time about 40% compared to the original plans; however, the estimated residence time was still about 1.5 seconds.

A statistical analysis of the NO_x emissions data was performed using MINITAB software. The results of this analysis showed that there was a statistically significant NO_x reduction when the combustion air was staged. However, the addition of the Covol reagents to the coal resulted in no statistically significant change in the NO_x emissions. The results of the off-line gas chromatographic analyses showed no detectable light hydrocarbons present in the flue gas for any fuel, with or without the Covol reagents.

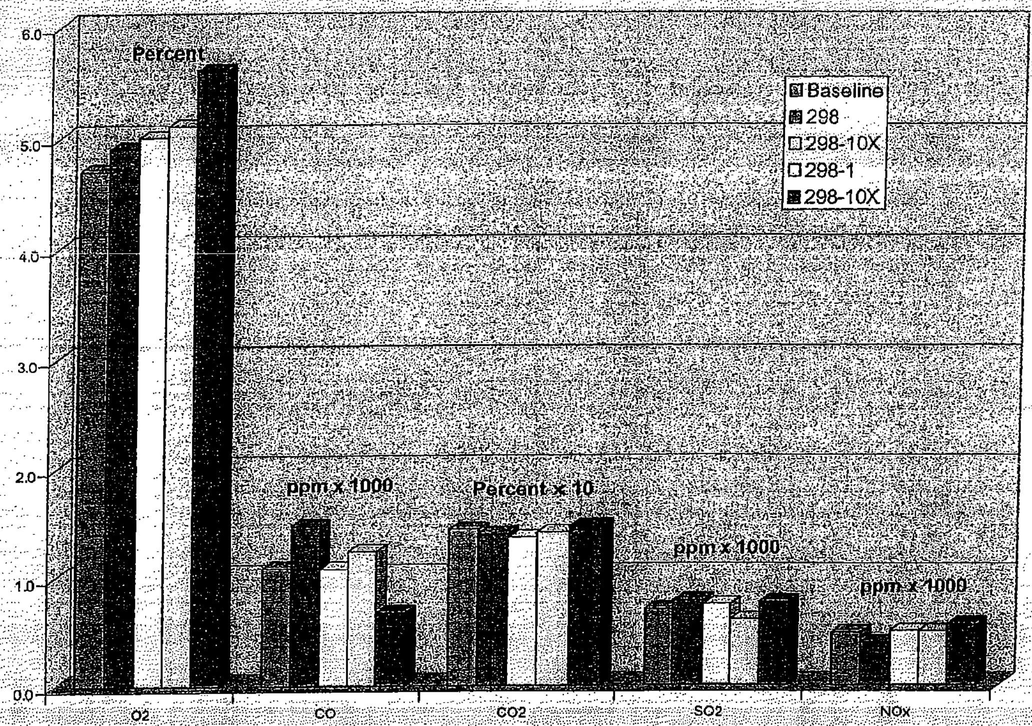


Figure 5. Emissions during drop-tube tests – no air staging

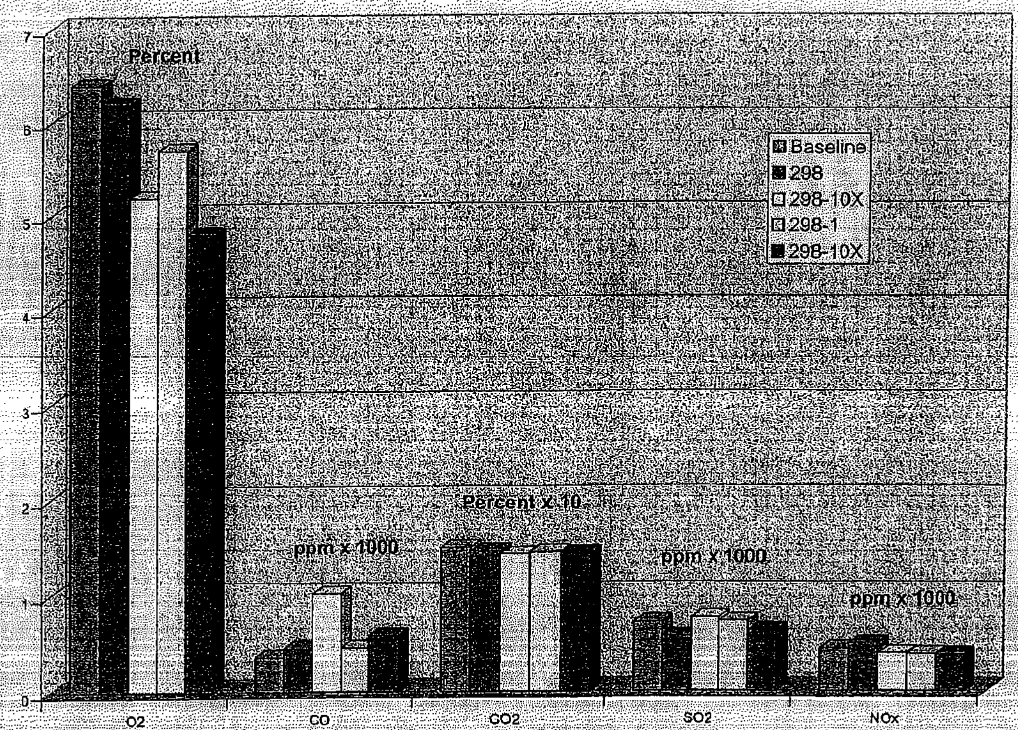


Figure 6. Emissions during drop-tube tests – with air staging

The results of the scanning electron and optical microscopy did not reveal any major differences that could be attributed to the presence of the two reagents or to their different concentrations (normal and 10X). There was not much difference recognized in the chars resulting from the two different drop-tube operating conditions (normal versus staged-air).

4.0 CONCLUSIONS

Based on the complete set of fuel characterization and bench-scale combustion tests, the following conclusions can be made:

- The addition of Covol 298 or 298-1 reagents to River Hill coal at normal dosage rates (2 lbs solids and 20 lbs water per ton coal) did not result in any adverse effect on fuel characteristics or combustion properties.
- The addition of Covol 298 or 298-1 reagents to River Hill coal at 10 times the normal dosage rates (20 lbs solids and 20 lbs water per ton coal) did not result in any adverse effect on fuel characteristics or combustion properties.
- Reagent addition did show a greater number of small particles agglomerating around the surface of larger coal particles suggesting that the reagent was acting as a dust suppressant and was effectively dispersed on the parent coal. This agglomerating effect increased as the dosage rate was increased.
- Proper sample preparation was critical to the success of the project. Analyses showed that each riffled sample did represent the parent coal. Mixing of the reagents with the River Hill coal was adequately done.
- Common coal analyses performed on all fuels showed that the four reagent-added fuels had values within one standard deviation of the parent coal for nearly all analyses.
- Combustion and deposition parameters calculated for each of the fuels were nearly identical suggesting that operation of the reagent-added fuels would be similar to the parent coal.
- Gaseous emission products from pyrolysis testing were similar between all fuels. Although the amount of NO_x precursors, ammonia and hydrogen cyanide, were slightly reduced during pyrolysis, the final NO_x emission levels measured from the drop-tube tests were not statistically different.
- Problems with the drop-tube furnace precluded any meaningful carbon-in-ash measurements from being made. Only the first two sections of the furnace could be used during these tests, thus reducing the residence time to about 1.5 seconds. High CO levels measured at the exit of the drop-tube and SEM micrographs showing carbon particles confirmed incomplete combustion.

5.0 RECOMMENDATIONS

The following recommendations are made based on the conclusions drawn from these characterization and bench-scale combustion tests:

- The larger, pilot-scale testing (>100 lbs/hr) should be investigated to confirm these laboratory and bench-scale results. These tests could be combined with other testing on a reduced number of fuels. This is based on the documented results that clearly show no adverse affect of either reagent on characterization or laboratory combustion analyses.
- Covol fuels should continue to pursue fabricating their own bench-scale combustion facility to perform characterization tests.
- After the bench-scale reactor is in operation, other coals utilizing the Covol reagents should be tested to confirm similar results as the River Hill coal.

5.0 REFERENCES

D. K. Johnson, et. al., "Coal Plus Binder Characterization and Testing", Final Report for Task 1. Fuel Characterization," The Energy Institute, The Pennsylvania State University, June 12, 2002.

M. A. Wojtowicz, et. al., "Thermogravimetric-Fourier Transform Infrared (TG-FTIR) Analysis of Coal and Synthetic Fuels," Advanced Fuel Research, July 23, 2002.

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